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DEMONSTRATION OF VEHICULAR VISIBLE LIGHT COMMUNICATION BASED ON LED HEADLAMP

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ABSTRACT−With the emergence of LED lighting, IT convergence technology using the visible spectrum of LEDs, such as Visible Light Communication (VLC), has been highlighted. Among the many VLC applications, vehicular VLCs based on LED headlamps and transportation lighting infrastructure, such as street lamps, traffic lights, etc., are considered good alternatives for Intelligent Transportation Systems (ITS) or Active Safety applications. This paper introduces a demonstration system of vehicle-to-vehicle (V2V) VLC based on LED headlamps. By applying an inverse 4-PPM modulation scheme satisfying a 75 % dimming level under the light distribution regulation of LED headlamp, the proposed system showed its capability for V2V VLC with a 10 kbps data rate for more than 30 m under day time conditions. By measuring the BER performance according to distance, outdoor V2V VLC was possible for more than 30 m even in the day time.

KEY WORDS : Light emitting diode (LED), LED headlamp, Visible light communication (VLC), Intelligent transportation systems (ITS), Vehicle-to-vehicle (V2V), IT convergence

1. INTRODUCTION

LED lighting has emerged as the next generation lighting. LED lighting has many benefits, such as a long life expectancy, low power consumption, high tolerance to humidity, high efficiency, and fast switching, compared to conventional lighting, such as incandescent and fluorescent lamps (Dupuis and Krames, 2008). Therefore, LEDs are used widely in indoor and outdoor applications, such as illumination lighting, automotive lighting and backlight units (BLUs) for digital signage and televisions. In particular, the fast switching of LEDs makes them applicable to data communication. As a consequence, LED-IT convergence technology using the visible spectrum of LEDs, such as Visible Light Communication (VLC), has emerged (Azhar *et al*., 2013; Grobe *et al*., 2013; Haigh *et al*., 2013; Jovicic *et al*., 2013; Moon and Jung, 2012; Yoo and Jung, 2013; Zhang *et al*., 2013). Recently, the IEEE standard association (IEEE Standard, 2011) published the corresponding VLC standardization. VLC can be applied in any place where LED lighting exists. Therefore, the most important consideration of VLC based on LED lighting is that it needs to transmit data while maintaining the original function of the LED as illumination lighting.

Among the possible VLC applications, the VLC for Intelligent Transformation Systems (ITS) has been considered widely and studied by many VLC research groups (Akanegawa *et al*., 2001; Choi *et al*., 2012; Kumar *et al*., 2011; Lee *et al*., 2012a, 2012b; Nagura *et al*., 2010; Pang and Liu, 2001; Premachandra *et al*., 2010; Takai *et al*., 2013; Yu *et al*., 2013). To realize intelligence in ITS, VLC needs to make use of Information and Communication Technologies (ICT). Among the possible ICTs, VLC is a good candidate because of its benefits. The first benefit is that transportation lighting infrastructures, such as street lamps, traffic lights, vehicular lamps, etc., are changing to LED lighting. Therefore, the installation costs for the construction of a VLC-based ITS environment can be reduced by reusing these transportation LED lighting infrastructures. Another benefit is that it has no electro-magnetic compatibility (EMC) / electro-magnetic interference (EMI) problems, which are quite serious problems in ITS based on the radio frequency (RF) signals. Finally, VLC-based ITS can be provided without considering the RF regulations and without interfering with other RF services.

The potential of V2V VLC communication using rear lamps has been confirmed in several papers (Kim *et al*., 2012; Takai *et al*., 2013, 2014; Yamazato *et al*., 2014). Recently, CAN based bidirectional V2V VLC was proposed to extend the usage of CAN in vehicular networks (Kim *et al*., 2012). However, it cannot guarantee the light distribution regulation of LED headlamps used commercially.

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Therefore, this study evaluated the possibility of vehicular vehicle-to-vehicle (V2V) VLC based on LED headlamps considering the lighting distribution regulation of headlamps under daytime conditions. To satisfy this light distribution regulation including proper control of the LED headlamp's heating problem, more than 70 % PWM dimming (less than full brightness) is required for LED headlamps. Because the Inverse 4-PPM modulation scheme can provide more than 70 % PWM dimming (75 % PWM dimming) with a twofold higher data rate than the VPPM provided by IEEE VLC standard (IEEE Standard, 2011), the Inverse 4-PPM for V2V VLC modulation scheme was used. Through experiments in the field, 10 kbps data rate (20 kHz optical rate of LED headlamp) with communication distance more than 30 m were achieved in a day time scenario.

2. SYSTEM DESCRIPTION

Figure 1 shows a block diagram of the vehicular V2V demonstration system. The serial input data (binary data) was mapped to a LED headlamp via a signal modulator. The modulated signal was transmitted to the receiver through the optical wireless channel. The received optical signal by PD (Photo-detector) can be demodulated by passing through an amplifier, filter and A/D converter.

2.1. Transmitter Sides

Figure 2 shows the transmitter prototype of the demonstration system, which is composed of a LED headlamp (Figure 2 (a)) and LED Driver Module (LDM) (Figure 2 (b)). The commercial prototype LED headlamp, which was designed for 'QM5' vehicle in Renault Samsung Motors, was used for transmitting the VLC signal. Therefore, it is designed to satisfy the regulation of the light distribution, such as the radiation pattern and radiation distance used in actual vehicles. To satisfy the distribution regulation criteria in real implementation, our LED headlamp supporting VLC capability was designed to provide 25 % more intensity strength than that required in distribution regulation criteria. Figure 2 (c) and (d) show the lighting distribution results of low and high beam of our LED headlamp. Under this regulation condition, the goal was to investigate the achievable communication performance according to the Tx-Rx distance under daytime conditions.

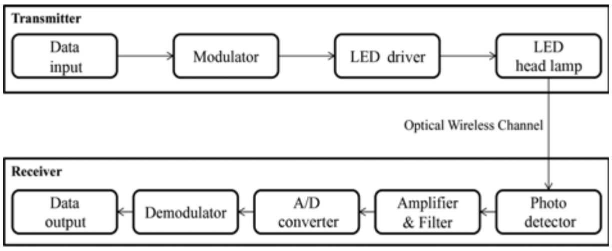
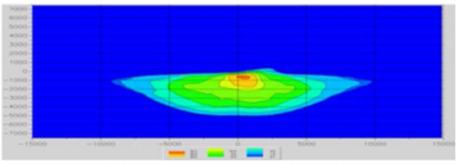


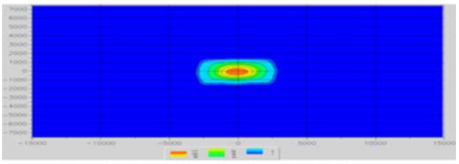
Figure 1. Overall block diagram of the vehicular V2V demonstration system.

(a) LED headlamp

(b) LED driver module (LDM)



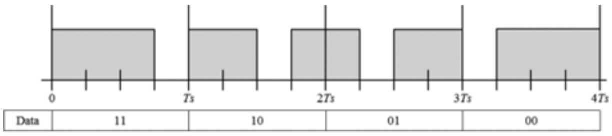
(c) Lighting distribution (Low beam)



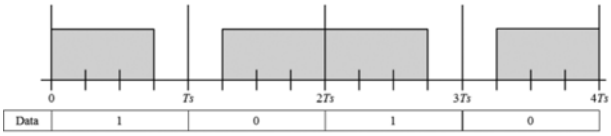
(d) Lighting distribution (High beam)

Figure 2. Transmitter prototype of demonstration system.

To control dimming in LED headlamps, the easy way is to use a pulse width modulation (PWM) scheme. Interestingly, PWM dimming helps the LED headlamp satisfy the thermal constraints needed for proper operation of the LED headlamps by controlling the amount of emitted light. For example, the actual LED headlamp operates a PWM with 70 % dimming to satisfy the thermal constraints. Therefore, an inverse M-ary Pulse Position Modulation (I-M-PPM) scheme was used to support both dimming control and data transmission. This is the inverse scheme of a conventional M-ary PPM scheme that makes it possible to control dimming to more than 50 % target dimming. Although the variable pulse position modulation (VPPM) scheme proposed in the VLC standard (IEEE Standard, 2011) is possible, the inverse M-ary PPM is better for increasing the data rate than VPPM, satisfying the target dimming level. For target dimming greater than 70 %, an inverse 4-PPM scheme was applied, providing a 75 % dimming level. Figure 3 shows the signaling example



(a) Inverse 4-PPM scheme



(b) VPPM scheme

Figure 3. Comparison of the signaling example.

of an inverse 4-PPM scheme and VPPM scheme. From Figure 3, the data rate of inverse 4-PPM was 2 times higher than that of VPPM. A greater than 10 kbps data rate can be achieved by operating the system with a 20 kHz optical rate in a LED headlamp.

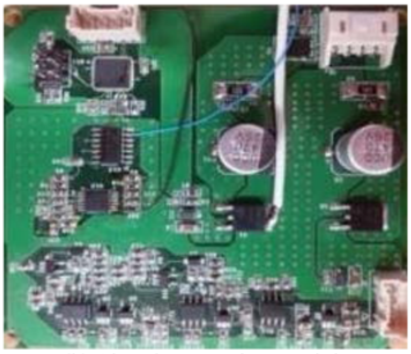
2.2. Receiver Sides

Figure 4 shows the receiver prototype used in the demonstration. Figure 4 (a) configures the photo-detector module, consisting of a photodiode, aperture, lens and color filter. Figure 4 (a) shows two PD modules (one is with lens and the other is without lens). The lower part (with lens) was used for the experiments (Red box in the figure). To collect the dispersed optical signal, the optical lens and aperture were installed in the photo-diode, which results in an extension of the communication distance.

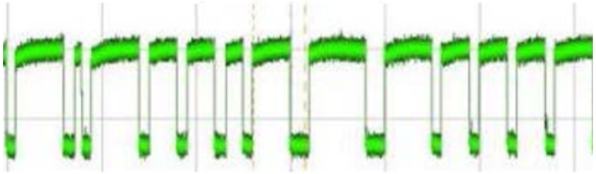
In the case of a V2V VLC demonstration in the day time, sunlight noise is the most dominant noise source. On the other hand, the most important problem in using a PD for optical signal detection is that it is difficult to separate each of the optical signals, the optical interference and noise, such as another light source and sunlight due to the IM/DD (Intensity modulation/Direct Direction) property of the photo-diode. In particular, the sunlight spectrum has been distributed in the range of all visible light, infrared and ultraviolet. To solve this problem, a color filter was placed on the lens to minimize the interfering spectrum range of sunlight noise. Without an optical filter, V2V VLC at daytime is difficult because the PD may be saturated by sunlight. In addition, the LED package produces light signal based on blue LED with a yellow phosphor. On the other hand, the use of a phosphor decreases the speed of the intensity change generated by the blue LED to transmit the VLC data. Therefore, the data transmission capability of V2V VLC can be enhanced by filtering the light signal using blue optical filter.

The spectrum of the color filter (bp500 by MIDOPT (BP500 Green-Blue Bandpass, 2003)) is between approximately 330 nm to 600 nm, as shown in Figure 5 (a), and the spectrum of the LED package (LE UW D1W4 01 by Osram (Osram Ostar Headlamp, 2003)) in the LED headlamp is between approximately 400 nm to 800 nm, as described in Figure 5 (b). Figure 5 (c) shows the spectral responsivity of the photodiode (bpw20rf by VISHAY (BPW20RF, 2011)).

(a) Photo detector module



(b) Signal processing module



(c) Measurement example of the received signal after passing through the optical filter and PD

Figure 4. Receiver prototype of demonstration system.

The MC9s12P32 Micro Controller Unit (MCU) of freescale was used to implement the LED driver module and the receiver signal processing module. This MCU is often used as the actual control and application of the vehicle, such as an advanced driver assistance system (ADAS), body electronics, chassis, and safety controls. Therefore, the problems generated by the electrical equipment of the vehicle can be minimized.

3. EXPERIMENT RESULTS

3.1. Experiment Setup

Figure 6 shows the experimental setup in an outdoor area in the daytime. The sun was located in the direction of approximately 30 degrees from the receiver. In this experiment, the distance between the transmitter and receiver was changed from 5 m to 40 m in 5 m intervals. As previously stated, the optical rate of the transmitter (LED headlamp) was set to 20 kHz.

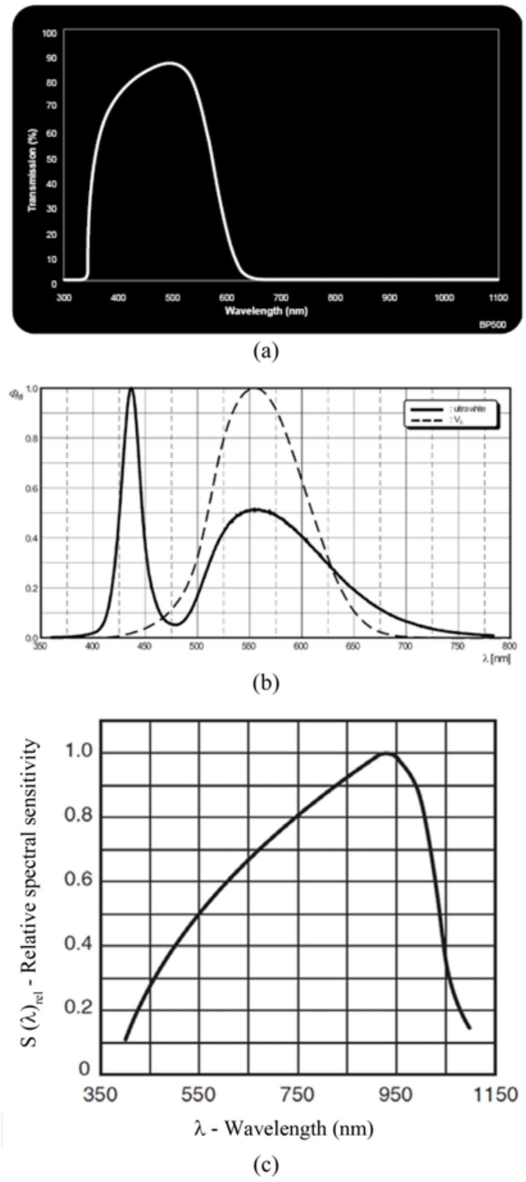


Figure 5. Spectrum of (a) Color filter; (b) LED packge; and (c) Photo-diode.

3.2. Results

One packet consisted of sync. (2 byte), header (1 byte) and data (1 byte), as shown in Figure 7.

Figure 8 configures the bit error rate (BER) and achievable data rate (ADR) with a communication distance of 20 m. If an obstacle exists between the transmitter and receiver, the system indicates the blocking and marks it as a black block, as shown in Figure 8. This block shows that the data is not detected in the receiver side by the obstacles. By showing the blocking period in Figure 8, V2V VLC can be shown to have obstacle recognition capability. Because the data recovery time after blocking is too short (much less than the blocking time period), it can be considered negligible.

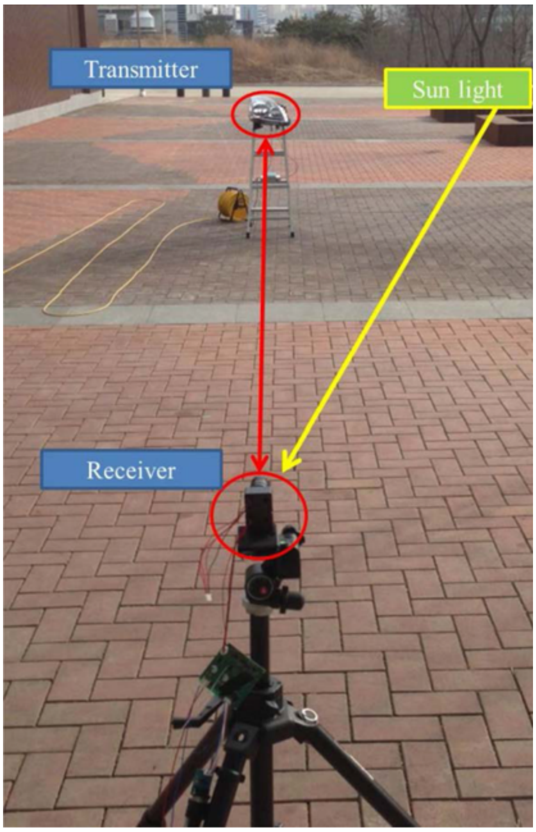


Figure 6. Experimental setup.

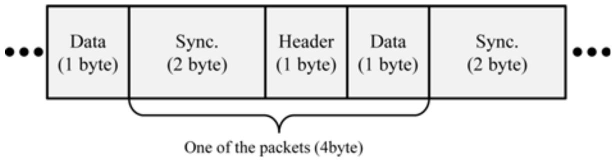


Figure 7. Structure of the data packet.

Figure 9 shows the block diagram of the obstacle indication mechanism. The received current signal $r(t)$, which is converted from the received optical signal $y(t)$ by the photo-diode, can be formulated as follows;

$$\begin{aligned} r(t) &= R \cdot y(t) \\ &= R \cdot \{X(t) \otimes h_o(t) + n_o(t)\} \\ &= H(0) \cdot x(t) \otimes h(t) + n(t) \end{aligned} \tag{1}$$

where $\otimes$ denotes the convolution, R is the PD conversion responsivity (A/W), $x(t)$ is the current signal, $X(t)$ is the light signal, $h_o(t)$ is impulse response of the optical signal channel, $n_o(t)$ is the optical noise, and $H(0)$ is the channel DC gain. $h(t)$ denotes the normalized electrical impulse response of the optical wireless channel and $n(t)$ is the electrical AWGN.

The receiver obtains the obstacle indication metric z, as shown below;

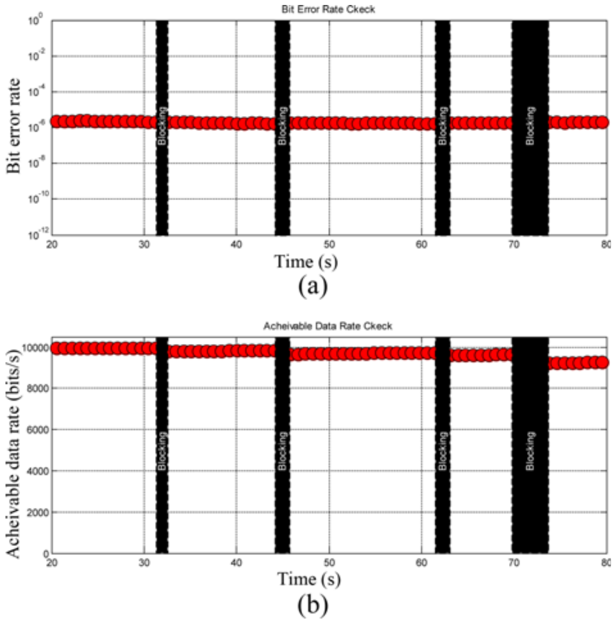


Figure 8. Demonstration system's (a) Bit error rate (BER) performance; and (b) Achievable data rate (ADR).

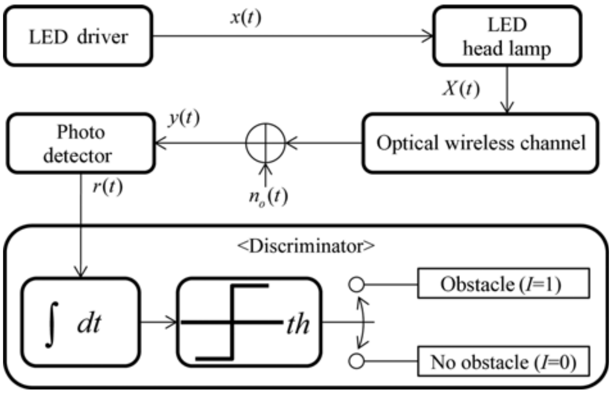


Figure 9. Block diagram of an obstacle indication.

$$z(t) = \frac{1}{T_s}\int_{iT_s}^{(i+1)T_s} r(t)\,dt \quad (i=0,1,2,\ldots). \tag{2}$$

Finally, the obstacle indicator I was determined in the discriminator to be

$$I = \begin{cases} 1, & z \le \delta_{\text{th}} \\ 0, & \text{otherwise} \end{cases} \tag{3}$$

where δ_{th} means the threshold value for the obstacle indication, which can be determined from the received signal without containing data ($r(t) = n(t)$) as follows;

$$\delta_{\text{th}} = \alpha \cdot \left[\frac{1}{N \cdot T_s} \int_{i \cdot T_s}^{(i+N)\cdot T_s} n(t)\,dt \right] \tag{4}$$

where α is the margin coefficient.

The Achievable Data Rate (ADR) is represented as a function of the maximum transmission data rate and the bit error rate (BER) as follows (Moon and Jung, 2012);

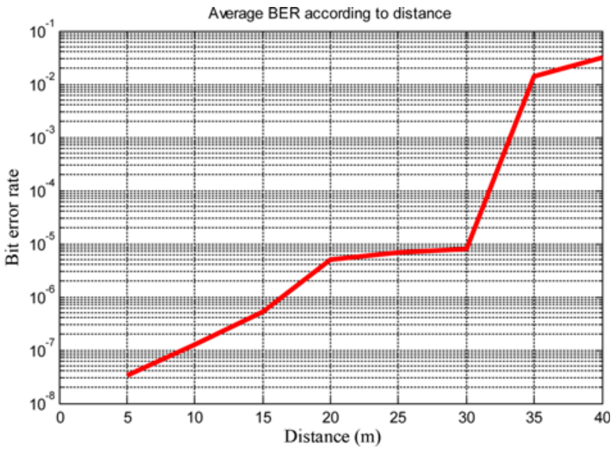


Figure 10. Average BER performance of system according to distance.

$$ADR = (1 - P_{\text{b}}) \cdot R_{\max} \tag{5}$$

where P_{b} is the bit error rate and $R_{\max}$ is the maximum transmission data rate per unit time (bits/s). Here, $R_{\max}$ is defined as follows;

$$R_{\max} = \frac{\text{total number of data bits per block to be transmitted } (bits)}{\text{time to transmit one data block using given modulation scheme } (\text{s})}. \tag{6}$$

As shown in Figure 8 (b), if there is no obstacle, ADR is approximately 10 kbps. On the other hand, the ADR decreased according to the data blocking time caused by obstacles because the blocking time affects the ADR in Equation (5).

Finally, Figure 10 shows the average BER performance according to the communication distance. The demonstration system could achieve a BER performance of 10^{-5} at a distance of up to a 30 m, even in the daytime. Therefore, this demonstration system proves that vehicular VLC is a possible solution for future ITS and active safety systems.

4. CONCLUSION

This paper introduced the vehicular V2V VLC demonstration system based on a LED headlamp. Using the inverse 4-PPM scheme with 75 % dimming under the light distribution regulation of LED headlamp, this system can transmit 10 kbps with a 20 kHz optical rate. A color filter was used in the receiver to avoid optical noise and interference, such as sunlight and other optical sources. To extend the communication distance, the lens and aperture were also constructed in the receiver. In addition to the blocking detection capability of the system, the vehicular VLC was found to be capable, even in the daytime, by showing a 10–5 BER at a communication distance of more than 30 m.

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